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DEVELOPMENT OF HEADFORMS FOR SIZING INFANTRY HELMETS

William D. Claus, Jr., et al

Army Natick Laboratories
Natick, Massachusetts

June 1974

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William D. Claus, Jr., Lawrence R. McManus, and Philip F. Durand

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13. ABSTRACT

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DEVELOPMENT OF HEADFORMS FOR SIZING INFANTRY HELMETS

by

William D. Claus, Jr.
Lawrence R. McManus
and
Philip E. Durand

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U.S. Army Natick Laboratories
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FOREWORD

This report describes work carried out as part of the Army Materiel Command Five Year Personnel Armor Program. Under the Armor Program, a broad AMC interlaboratory helmet and body armor technical effort was mounted to support the design and development of improved armor end items. One of the basic problems which was addressed was head anthropometrics. New techniques for defining and measuring head shapes were developed and applied to the fabrication of a set of first generation plaster headforms over which close-fitting helmets were designed. These techniques have wide application in the design of military and civilian protective headgear.

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ABSTRACT

A new technique for defining and measuring head shapes was developed and applied in the fabrication of a set of first generation plaster headforms. The design of a unique head measuring device is reported. The device is a clear polycarbonate hemisphere on which are mounted twenty-seven moveable mechanical probes. The hemisphere is placed over a subject's head, and the probes are moved to contact the head and thus define head shape. The probe data from a population of Army men were reduced statistically to yield generalized head shapes. The feasibility of combining this probe technique with classical anthropometric head measurements to yield generalized head shapes of various sizes was demonstrated. A set of first generation headforms was sculptured using specified probe data. Improvements and extensions of the present study are indicated.

1. INTRODUCTION

The work described in this report represents one of many interdisciplinary technical efforts carried out as part of the AMC Five Year Personnel Armor Program. Two of the goals of the infantry helmet portion of the Armor Program are to develop a helmet that is more stable and has a higher troop acceptability than the current standard M-1 helmet. The M-1 helmet is issued in only one large size, and is often referred to, not surprisingly, as a "pot." The introduction of a multiple sized helmet is expected to contribute significantly toward attaining the aforementioned goals.

Fitting a rigid helmet made from ballistic protective materials is immediately complicated by the fact that human heads are extremely variable in size and shape. The most recent description of relevant head dimensions of the Army population is reported by White and Churchill (1971). An indication of the severity of the design problem is that the ranges of measurements reported by White and Churchill are, for example, 128 mm for head circumference, 58 mm for head length, 46 mm for head breadth, and 60 mm for head height. These variations in head dimensions obviously lead to large degrees of misfit for many individuals wearing the one size M-1 helmet.

The goal of this work was to develop a set of suitably shaped headforms based on US Army population measurements for use by helmet designers. In this report, several related efforts to quantify head sizes and shapes are described. A beginning was made by others on a mathematical model of the head and it was adapted for use here. An algorithm for sorting head dimensions was developed at the Ballistics Research Laboratories and is summarized in Section 2. Several different approaches to defining head shapes are described in Section 3. The design and operation of the technique ultimately used, a unique head measuring device, in developing the headforms is also reported in that section. An account of the development of the headforms themselves is contained in Section 4, including the probe definition of surfaces and the sculpturing technique. Conclusions are presented in Section 5.

2. AN ALGORITHM FOR SORTING HEAD DIMENSIONS

In order to develop a sizing system for any piece of clothing or personal equipment, the total variation in relevant body dimensions must be considered. Then, using a predetermined criterion, the dimensional ranges are divided into categories or "sizes." Classically, percentile values are used to arrive at such subdivisions. See, for example, Ziegen, et. al. (1960). A major weakness in the percentile approach is that there are no convincing reasons why one particular percentile should be chosen over another in subdividing the population under consideration.

Rather than arbitrarily select head percentile values, a start on a mathematical model of the head was made at the Ballistics Research Laboratories, Aberdeen, MD. The first step in the development of that model was to formulate an algorithm for sorting subjects into categories according to prescribed rules. That study was accomplished by Goulet and Sacco (1972).

Anthropometric data from a given head was treated as a measurement vector with components such as head length and head circumference and with a practical limit of seven dimensions (according to unpublished work). To develop the sorting rule, a concept of "mismatch" was introduced and defined in this context to be the sum of the arithmetic differences between the components of a measurement vector and its size vector.

The total mismatch is similarly defined for the total population under consideration. The total mismatch is the quantity to be minimized by the selection of a good sizing system. Dynamic and non-linear programming techniques were used to determine optimum size vectors. The reader is referred to Goulet and Sacco (1972) for additional details concerning the techniques used in developing the size vectors.

The algorithm was applied to the head measurement data of the population of 500 Army aviators reported by White (1961). Raw measurement vectors consisting of four components, circumference, length, breadth, and height, were used to generate size systems consisting of one through nine sizes.

The sizing solutions from Goulet and Sacco (1972) for systems consisting of one through nine sizes using dynamic and nonlinear programming techniques are listed in Tables I, II, and III. The solutions in Tables I and II are in standard deviation units. The information in Table IV from White (1961) is needed to convert from standard deviation units to either millimeters or inches. Small differences between Table IV and White and Churchill (1971) are neglected here for helmet sizing purposes.

The curves in Figure 1 quantify, according to the viewpoint of this algorithm, the idea that a population is better fitted, i.e., has less overall mismatch, with a larger number of sizes than with a few sizes. Large differences in mismatch are evident in going from two to five sizes, while the rate of return is nearly constant beyond five sizes.

As noted above, the sizing solutions of Goulet and Sacco in Table III are based on a population of 500 subjects because those data were readily available. A comparison was run using the US Army 1966 Survey population of 6630 subjects, and it was concluded that N=500 was large enough to achieve numerical stability in the sizing solutions (personal communication from Dr. Harvey, BRL). The ramifications of this study are elaborated on in later sections of this report.

TABLE IV

MEANS AND STANDARD DEVIATIONS OF FOUR HEAD DIMENSIONS

(White, 1961)

	Mean (mm)	Std. Dev. (mm)
Head Circumference	571.2	13.8
Head Length	197.4	6.8
Head Breadth	155.4	5.4
Head Height	126.6	6.4

TABLE I. Dynamic Programming Solutions
(Standard Deviation Units from Goulet & Sacco, 1972)

Number of Sizes	Height	Width	Length	Circum-ference	Number of Heads	Percent Sample	Percent Total	MMM*	MMM/dim.
1	3.0	3.0	3.0	3.0	492	100.0	98.4	1944.1	3.02
2	3.0	3.0	3.0	3.0	159	32.3	31.8	3280.1	1.67
	1.0	1.0	1.0	1.0	333	67.7	66.6		
3	3.0	3.0	3.0	3.0	68	13.8	13.6	2619.3	1.33
	1.6	1.6	1.6	1.6	208	42.3	41.6		
	.5	.5	.5	.5	216	43.9	43.2		
4	3.0	3.0	3.0	3.0	47	9.5	9.4	2303.3	1.17
	1.8	1.8	1.8	1.8	112	22.8	22.4		
	1.0	1.0	1.0	1.0	150	30.5	30.0		
	.4	.4	.4	.4	183	37.2	36.6		
5	3.0	3.0	3.0	3.0	68	13.8	13.6	2111.3	1.07
	1.8	1.8	1.8	1.8	91	18.5	18.2		
	1.0	1.0	1.0	1.0	117	23.8	23.4		
	.5	.5	.5	.5	133	27.0	26.6		
	-.1	-.1	-.1	-.1	83	16.9	16.6		
6	3.0	3.0	3.0	3.0	83	16.9	16.6	1966.5	1.00
	2.1	2.1	2.1	2.1	133	27.0	26.6		
	1.6	1.6	1.6	1.6	117	23.8	23.4		
	1.0	1.0	1.0	1.0	91	18.5	18.2		
	.5	.5	.5	.5	48	9.7	9.6		
	-.1	-.1	-.1	-.1	20	4.1	4.0		
7	3.0	3.0	3.0	3.0	10	2.0	2.0	1905.3	.97
	2.3	2.3	2.3	2.3	37	7.5	7.4		
	1.8	1.8	1.8	1.8	48	9.7	9.6		
	1.4	1.4	1.4	1.4	64	13.0	12.8		
	1.0	1.0	1.0	1.0	117	23.8	23.4		
	.5	.5	.5	.5	133	27.0	26.6		
	-.1	-.1	-.1	-.1	83	16.9	16.6		
8	3.0	3.0	3.0	3.0	10	2.0	2.0	1848.5	.94
	2.3	2.3	2.3	2.3	37	7.5	7.4		
	1.8	1.8	1.8	1.8	48	9.7	9.6		
	1.4	1.4	1.4	1.4	64	13.0	12.8		
	1.0	1.0	1.0	1.0	81	16.5	16.2		
	.7	.7	.7	.7	69	14.0	13.8		
	.4	.4	.4	.4	100	20.3	20.0		
	-.1	-.1	-.1	-.1	83	16.9	16.6		
9	3.0	3.0	3.0	3.0	10	2.0	2.0	1808.5	.92
	2.3	2.3	2.2	2.3	37	7.5	7.4		
	1.8	1.8	1.8	1.8	48	9.7	9.6		
	1.4	1.4	1.4	1.4	64	13.0	12.8		
	1.0	1.0	1.0	1.0	81	16.5	16.2		
	.7	.7	.7	.7	69	14.0	13.8		
	.4	.4	.4	.4	100	20.3	20.0		
	-.1	-.1	-.1	-.1	63	12.8	12.6		
	-.6	-.6	-.6	-.6	20	4.1	4.0		

*Mean Minimum Miss-Match

TABLE II. Nonlinear Programming Solutions
(Standard Deviation Units from Goulet and Sacco, 1972)

Number of Sizes	Height	Width	Length	Circumference	Number of Heads	Percent Sample	Percent Total	MMM*	MMM/dim.
1	3.0	2.7	3.0	2.8	491	100.0	98.2	5731.9	2.92
2	3.0	2.7	3.0	2.9	168	34.2	33.6	3144.0	1.60
	1.0	1.0	1.1	.8	323	65.8	64.6		
3	3.0	2.7	3.0	2.9	63	12.8	12.6	2572.3	1.31
	1.6	1.6	1.7	1.6	213	43.4	42.6		
	.5	.5	.5	.6	215	43.8	43.0		
4	3.0	2.7	3.0	2.9	38	7.7	7.6	2212.9	1.13
	1.9	1.8	1.7	2.0	116	23.6	23.2		
	1.0	1.0	1.0	.8	142	28.9	28.4		
	.4	.5	.4	.4	195	39.7	39.0		
5	3.0	2.7	3.0	2.9	38	7.7	7.6	2047.6	1.04
	1.9	1.8	1.7	2.0	111	22.6	22.2		
	1.0	1.0	1.1	1.0	120	24.4	24.0		
	.5	.5	.5	.6	146	29.7	29.2		
	-.1	-.1	-.1	-.2	76	15.5	15.2		
6	3.0	2.7	3.0	2.9	22	4.5	4.4	1914.6	.97
	2.1	2.1	2.0	2.0	46	9.4	9.2		
	1.6	1.6	1.6	1.6	86	17.5	17.2		
	1.0	1.0	1.1	.8	124	25.3	24.8		
	.5	.5	.5	.4	137	27.9	27.4		
	-.1	-.1	-.1	-.2	76	15.5	15.2		
7	3.0	2.7	3.0	2.9	8	1.6	1.6	1854.9	.94
	2.3	2.3	2.3	2.4	30	6.1	6.0		
	1.9	1.8	1.7	2.0	46	9.4	9.2		
	1.6	1.4	1.4	1.4	70	14.3	14.0		
	1.0	1.0	1.1	.8	129	26.3	25.8		
	.5	.5	.5	.3	132	26.9	26.4		
	-.1	-.1	-.1	-.2	76	15.5	15.2		
8	3.0	2.7	3.0	2.9	8	1.6	1.6	1772.1	.90
	2.3	2.3	2.3	2.4	30	6.1	6.0		
	1.9	1.8	1.7	2.0	46	9.4	9.2		
	1.6	1.4	1.4	1.4	70	14.3	14.0		
	1.0	1.0	1.1	.8	79	16.1	15.8		
	.8	.7	.5	.7	75	15.3	15.0		
	.4	.5	.5	.1	107	21.8	21.4		
	-.1	-.1	-.1	-.2	76	15.5	15.2		
9	3.0	2.7	3.0	2.9	8	1.6	1.6	1731.5	.88
	2.3	2.3	2.3	2.4	30	6.1	6.0		
	1.9	1.8	1.7	2.0	46	9.4	9.2		
	1.6	1.4	1.4	1.4	70	14.3	14.0		
	1.0	1.0	1.1	.8	79	16.1	15.8		
	.8	.7	.5	.7	75	15.3	15.0		
	.4	.5	.4	.1	101	20.6	20.2		
	-.1	-.1	-.1	-.1	64	13.0	12.8		
	-.6	-.6	-.6	-1.0	18	3.7	3.6		

*Mean Minimum Miss-Match

TABLE III. Sizing Solutions in Millimeters
(From Goulet and Sacco, 1972)

Number of Sizes	DYNAMIC PROGRAM				NONLINEAR PROGRAM			
	Height	Width	Length	Circum-ference	Height	Width	Length	Circum-ference
1	145.8	171.6	217.9	612.8	145.8	170.0*	217.9	610.0*
2	145.8	171.6	217.9	612.8	145.8	170.0*	217.9	611.4*
	133.0	160.8	204.2	585.1	133.0	160.8	204.9*	582.3*
3	145.8	171.6	217.9	612.8	145.8	170.0*	217.9	611.4*
	136.8	164.1	208.3	593.4	136.8	164.1	209.0*	593.4
	129.8	158.1	200.8	578.2	129.8	158.1	200.8	579.5*
4	145.8	171.6	217.9	612.8	145.8	170.0*	217.9	611.4*
	138.1	165.1	209.7	596.2	138.7*	165.1	209.0*	598.9*
	133.0	160.8	204.2	585.1	133.0	160.8	204.9*	582.3*
	129.2	157.5	200.1	576.8	129.2	158.1*	200.1	576.8
5	145.8	171.6	217.9	612.8	145.8	170.0*	217.9	611.4*
	138.1	165.1	209.7	596.2	138.7*	165.1	209.0*	598.9*
	133.0	160.8	204.2	585.1	133.0	160.8	204.9*	585.1
	129.8	158.1	200.8	578.2	129.8	158.1	200.8	579.5*
	126.0	154.8	196.7	569.8	126.0	154.8	196.7	568.5*
6	145.8	171.6	217.9	612.8	145.8	170.0*	217.9	611.4*
	140.0	166.8	211.7	600.3	140.0	166.8	211.0	592.9*
	136.8	164.1	208.3	593.4	136.8	164.1	208.3	593.4
	133.0	160.8	204.2	585.1	133.0	160.8	204.9*	582.3*
	129.8	158.1	200.8	578.2	129.8	158.1	200.8	576.8*
	126.0	154.8	196.7	569.8	126.0	154.8	196.7	568.5
7	145.8	171.6	217.9	612.8	145.8	170.0*	217.9	611.4*
	141.3	167.8	213.1	603.1	141.3	167.8	213.1	604.5*
	138.1	165.1	209.7	596.2	138.7*	165.1	209.0	598.9*
	135.6	163.0	206.9	590.6	136.8*	163.0	206.9	590.6
	133.0	160.8	204.2	585.1	133.0	160.8	204.9*	582.3*
	129.8	158.1	200.8	578.2	129.8	158.1	200.8	575.4*
	126.0	154.8	196.7	569.8	126.0	154.8	196.7	568.5*
8	145.8	171.6	217.9	612.8	145.8	170.0*	217.9	611.4*
	141.3	167.8	213.1	603.1	141.3	167.8	213.1	604.5*
	138.1	165.1	209.7	596.2	138.7*	165.1	209.0*	598.9*
	135.6	163.0	206.9	590.6	136.8*	163.0	206.9	590.6
	133.0	160.8	204.2	585.1	133.0	160.8	204.9*	582.3*
	131.1	159.2	202.2	580.9	131.7*	159.2	200.8	580.9
	129.2	157.2	200.1	576.8	129.2	158.1*	200.8*	572.6*
	126.0	154.8	196.7	569.8	126.0	154.8	196.7	568.5*
9	145.8	171.6	217.9	612.8	145.8	170.0*	217.9	611.4*
	141.3	167.8	213.1	603.1	141.3	167.8	213.1	604.5*
	138.1	165.1	209.7	596.2	138.7*	165.1	209.0*	598.9*
	135.6	163.0	206.9	590.6	136.8	163.0	206.9	590.6
	133.0	160.8	204.2	585.1	133.0	160.8	204.9	582.3
	131.1	159.2	202.2	580.9	131.7*	159.2	200.8*	580.9
	129.2	157.5	200.1	576.8	129.2	158.1*	200.1	572.6*
	126.0	154.8	196.7	569.8	126.0	154.8	196.7	569.8
	122.8	152.1	193.3	562.9	122.8	152.1	193.3	557.4*

**Points of difference between Dynamic Program and Nonlinear Program.*

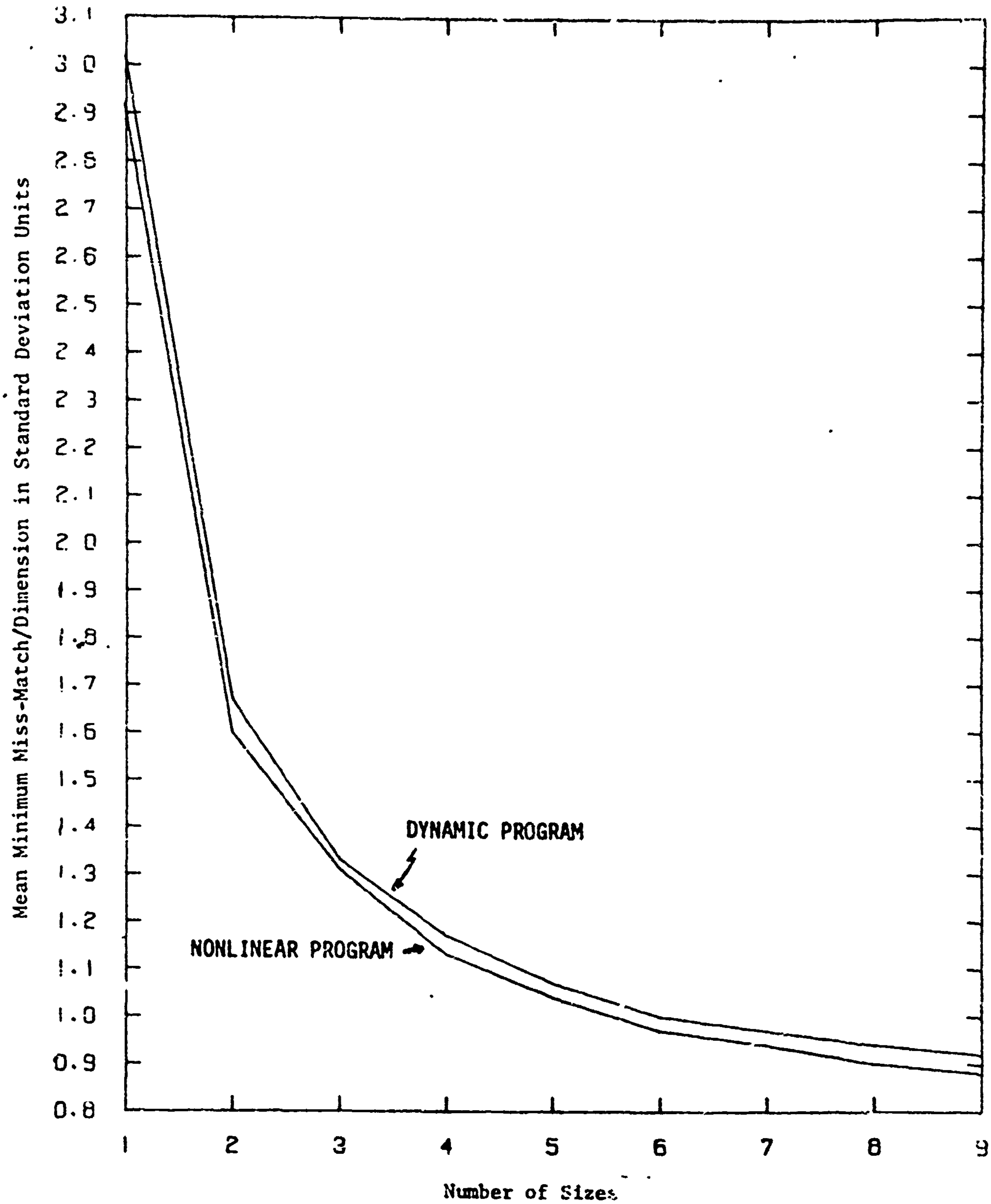

Figure 1. Sizing Errors - Sample 500 Army Aviators

3. HEAD SURFACE TECHNIQUES

Existing anthropometric head data suffer from a major deficiency from a helmet design point of view - the spatial relationship between standard landmarks is unknown. Classically, only distances from point to point are measured, either in a straight line or along an arc. Data are reduced statistically for each measurement separately, and the spatial inter-relationship between landmarks is lost. For example, head length and head height are often measured in a survey and the data are statistically reduced. In this process, the spatial relationships between the glabella, occiput, tragus and vertex are lost. In order to design a close-fitting helmet, the relative positions of those landmark locations are important. In this section, four approaches, Prince Charming, cast molding, digitizing, and a head measuring device, to defining head surfaces are described.

a. Prince Charming Concept

The size categories which were generated by the BRL algorithm are four dimensional - a three dimensional box plus an inscribed curvilinear circumference. To obtain head surface information, individuals were sought whose heads had very nearly the same physical four dimensions as the computer generated size categories. Such an individual, who was referred to as a "Prince Charming", would provide one head surface to fill in between anthropometric landmarks.

The search for Prince Charmings began by taking the four basic head dimensions, circumference, length, breadth and height, on 591 US Army men at Ft. Devens, Massachusetts during January 1972. Selected statistics of those measurements are reported in Table V. Of the 591 subjects measured, the individuals which resulted in the least mismatch (totalled over the four dimensions) from the size categories were identified as the "Prince Charmings".

TABLE V

STATISTICS ON 591 U.S. ARMY MEN - FT. DEVENS, MA

	Mean (mm)	Std. Dev. (mm)
Head Circumference	567	16.5
Head Length	196	7.6
Head Breadth	153	5.6
Head Height	127	7.0

BRL identified fourteen original Prince Charmings. Unfortunately, shortly after the measurements were taken, five of the Prince Charmings were either out of the Army or overseas, and one was unavailable for further measurement. BRL further recommended five alternates to be used for later work. The head dimensions of the thirteen subjects who were used for the additional measuring described below are listed in Table VI.

TABLE VI

HEAD DIMENSIONS OF PRINCE CHARMINGS

Subject No.	C (millimeters)	L (millimeters)	B (millimeters)	H (millimeters)	C (std. dev. units)	L (std. dev. units)	B (std. dev. units)	H (std. dev. units)
1	553	192	151	133	-.5	-.4	-.3	0.1
2	555	193	151	130	-.4	-.2	-.3	-.3
3	560	194	151	130	-.1	-.1	-.3	-.3
4	560	195	152	135	-.1	0.0	-.1	0.3
5	562	194	154	136	0.1	-.1	0.2	0.5
6	566	193	152	134	0.3	-.2	-.2	0.2
7	571	200	154	138	0.6	0.7	0.2	0.7
8	572	199	161	139	0.7	0.6	1.4	0.8
9	575	198	155	138	0.9	0.5	0.4	0.7
10	586	203	156	138	1.5	1.1	0.6	0.7
11	590	204	156	134	1.8	1.3	0.4	0.7
12	593	209	160	137	2.0	2.0	1.2	0.6
13	605	210	166	135	2.7	2.1	2.3	0.3

b. Cast Molding

The shapes of the Prince Charming heads were obtained in a direct fashion by plaster casting. Plaster of paris saturated gauze strips of a type commonly used to set broken limbs were used to mold the upper part of a subject's head. The head was protected by a thin rubber cap stretched with weights to fit snugly and mat the hair. A female mold was thus obtained and was utilized in making a male, Hydrostone casting. The head surfaces resulting from this technique include a small contribution from matted hair. Utilization of shaved heads was not feasible.

c. Digitizing

The problem of hair contributing to the cast molded head surface was circumvented by an alternate technique using a three-axis coordinate measuring machine. This machine measures the three cartesian coordinates of a selected spatial point which is defined by a sharp metal stylus. The coordinates are recorded on a punched paper tape. Approximately 400 points were taken on each head after the cast molding of the head described above. The stylus penetrated the subject's hair and the coordinate data represent the actual head surface.

The head data were processed into a control tape containing instructions to operate a numerically controlled milling machine. The control tapes were prepared by A. S. Thomas Inc., Westwood, MA and the headforms were cut on equipment at the AVCO plant in Stratford, Connecticut. The wooden headforms were cut as sectionalized molds suitable for use in vacuum forming operations. An example headform mold is shown in Figure 2. The details of this effort are reported by Claus, McManus and Durand (1974).

d. Head Measuring Device

The "Prince Charming" method and the various methods used to describe each Prince Charming's head still left the helmet developers short of a generalized shape for the sizing category that each Prince Charming represented. Therefore a device was conceived and constructed which would provide data for the generalization of the shape of the heads for each size category. This device, called the 3 Dimensional Surface Descriptor, is described below.

The device, shown in Figure 3, essentially consists of a moveable, transparent hemispherical shell on which measuring probes are mounted. The subject's (S's) head is immobilized by a bite bar, and the shape information is obtained by gently moving the probes until firm contact is made with the S's head. The midsaggital plane, right tragus, and right external canthus are used to reference the S's head with respect to the equitorial plane and polar plane of the hemisphere as shown in Figure 4. The X, Y, Z axes are actually orthogonal Cartesian axes. The X-axis is aligned with the right tragus; the additional line in the X-Y plane is intended to represent the fact that the right tragus and external canthus both lie in the equatorial plane. This technique spatially relates each measured point to every other measured point, thus yielding the three dimensional shape information.

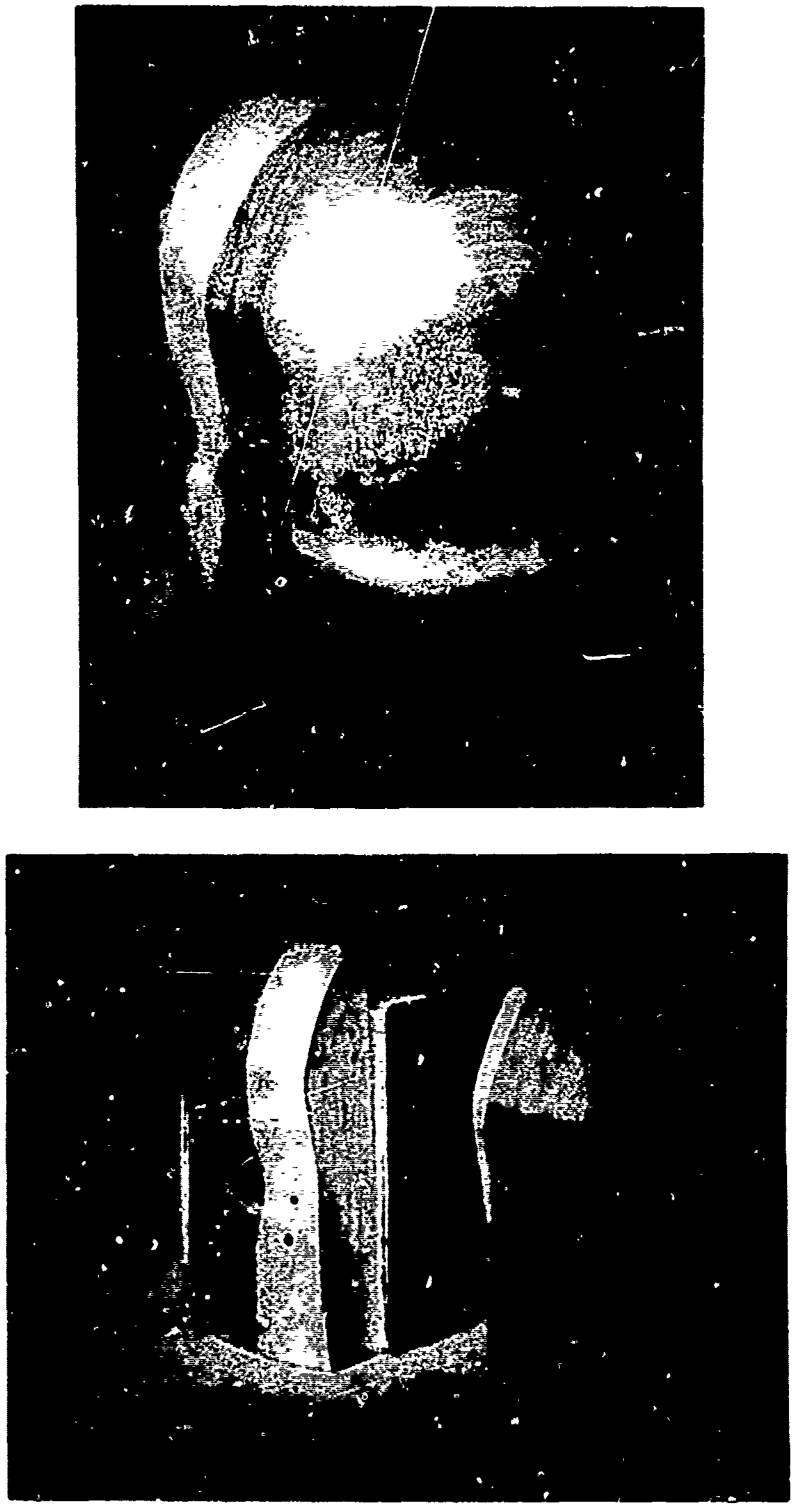

Figure 2. Example N/C Machined Headform Mold with Vacuum Ports: (a) Front View, (b) Exploded View

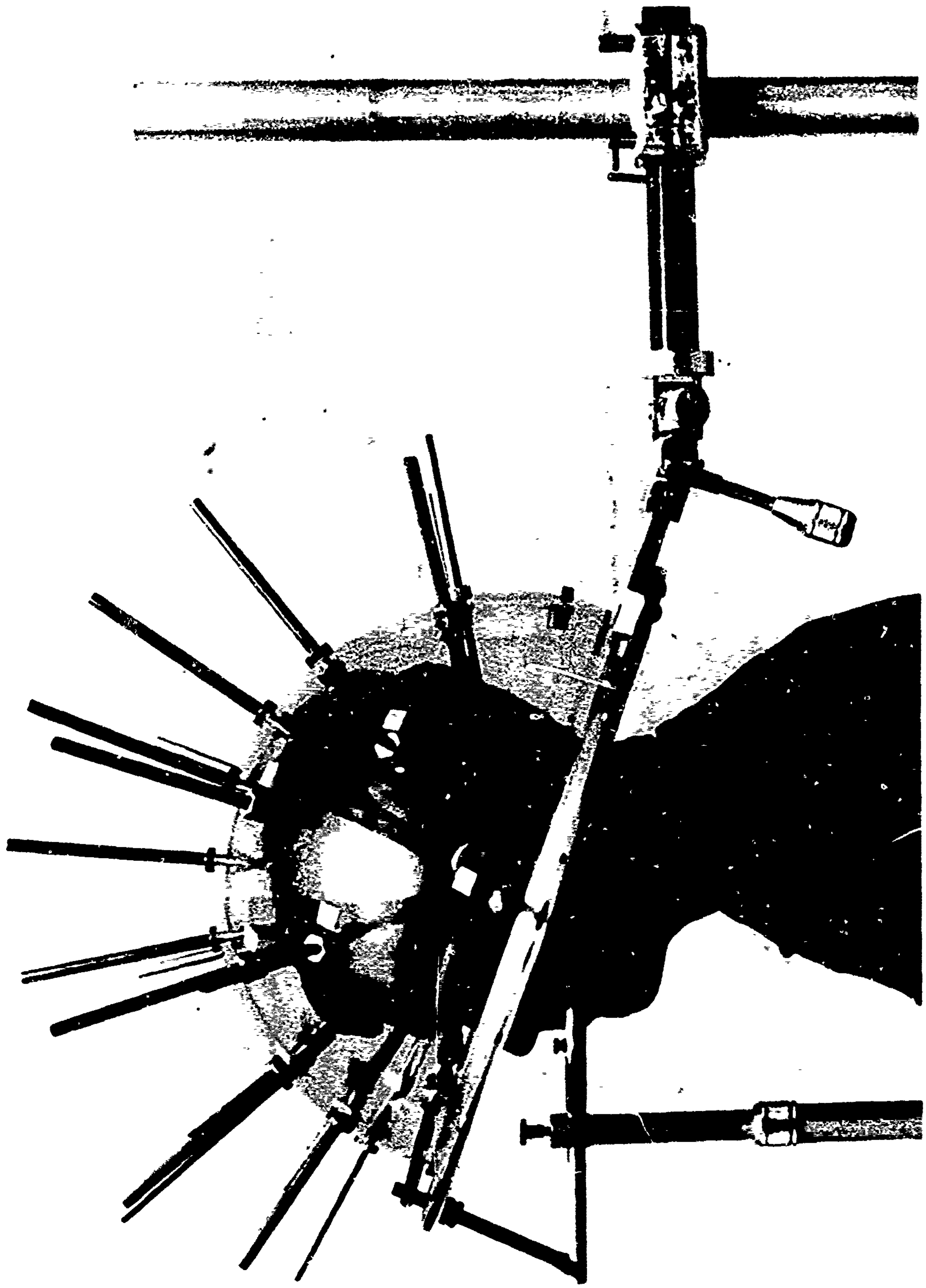

Figure 3. Head Measuring Device

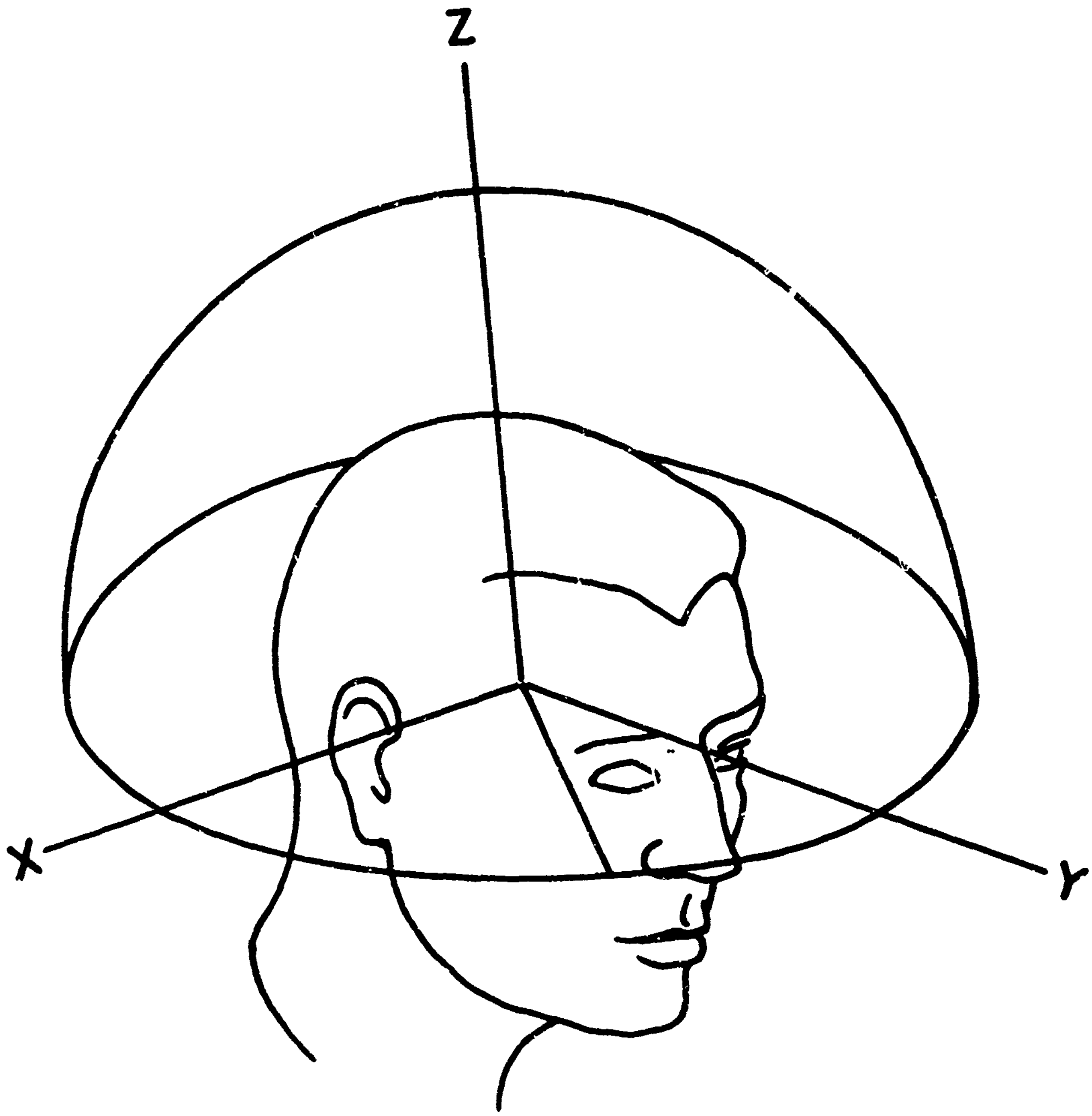

Figure 4. Coordinate System for Referencing Head Measuring Device

The locations of the probes are given in Table VII in terms of spherical coordinates related to the Cartesian axes. The aximuth θ lies in the X-Y plane and is measured from the X-axis, and the elevation ϕ is measured from the X-Y plane.

TABLE VII

SPHERICAL COORDINATES OF PROBE LOCATIONS

Probe Number	θ (radians)		ϕ (radians)	
1	0	(0°)	0	(0°)
2 (moveable)	$\pi/18 - \pi/4$	(10° -45°)	0	(0°)
3 (moveable)	$\pi/2$	(90°)	$0 - \pi/9$	(0° - 20°)
4 (moveable)	$3\pi/4 - 17\pi/18$	(135° - 170°)	0	(0°)
5		(180°)	0	(0°)
6	$3\pi/2$	(270°)	$\pi/6$	(30°)
7	$\pi/2$	(90°)	$\pi/6$	(30°)
8	$\pi/2$	(90°)	$\pi/3$	(60°)
9	$\pi/2$	(90°)	$5\pi/12$	(75°)
10	$\pi/2$	(90°)	$\pi/2$	(90°)
11	$3\pi/2$	(270°)	$7\pi/12$	(105°)
12	$3\pi/2$	(270°)	$2\pi/3$	(120°)
13	$3\pi/8$	(67.5°)	$\pi/12$	(15°)
14	$3\pi/8$	(67.5°)	$\pi/6$	(30°)
15	$\pi/4$	(45°)	$\pi/4$	(45°)
16	$\pi/8$	(22.5°)	$\pi/6$	(30°)
17	0	(0°)	$\pi/3$	(60°)
18	$15\pi/8$	(337.5°)	$\pi/6$	(30°)
19	$13\pi/8$	(292.5°)	$\pi/6$	(30°)
20	$5\pi/8$	(112.5°)	$\pi/12$	(15°)
21	$5\pi/8$	(112.5°)	$\pi/6$	(30°)
22	$3\pi/4$	(135°)	$\pi/4$	(45°)
23	$7\pi/8$	(157.5°)	$\pi/6$	(30°)
24	π	(180°)	$\pi/3$	(60°)
25	$9\pi/8$	(202.5°)	$\pi/6$	(30°)
26	$11\pi/8$	(247.5°)	$\pi/6$	(30°)
27	$3\pi/2$	(270°)	$\pi/18$	(10°)

Using the fixture shown in Figure 3 to measure a group of subjects, the raw data are the lengths of the probes extending beyond the mounting bushings outer surfaces. At each probe, the bushing height and shell thickness must be accounted for in order to derive the ray length from the origin of the coordinate system shown in Figure 4.

4. DEVELOPMENT OF SIZED HEADFORMS

A useful representational form of anthropometric data for helmet designers is in rigid, full scale headforms as noted by Alexander et. al. (1961). The physical bases which the headforms represent must be understood by the designer in order to correctly utilize the headforms in solving a particular helmet problem, such as the design of a football helmet, a racing car driver's helmet, or in this application, an infantryman's helmet. In the following sections, the rationale used in developing the headform dimensions is presented, and the procedures used by the sculptor in translating the numerical data into plaster headforms are described.

a. Probe Definition of Surfaces

The device shown in Figure 3 was used to measure approximately one hundred subjects at Fort Devens, MA during February 1973. In addition to the probe readings, four standard head measurements (circumference, length, breadth and height) were taken on each subject. Selected statistics of those measurements are presented in Table VIII.

In addition to the probe data, which are unique to the particular fixture design, universal ray data are also listed. These data are referred to the spherical coordinate system shown in Figure 4 and are independent of the fixture geometry. Ray readings, not probe readings, are an inherent property of head geometry. For example, if a cubical measuring device were utilized having the same reference orientation as the hemispherical device, probe readings from the two devices would differ but the resultant ray readings would be identical.

In computing the total population statistics, for all of the probes except Probe 27 the number of subjects was 106. Probe 27 was added after the first day of measuring in order to extend the measurement coverage at the back of the head. For Probe 27, N=69.

TABLE VIII

TOTAL POPULATION STATISTICS (N=106)

Probe No.	Probe Values (mm) Mean	Probe Values (mm) Std. Dev.	Ray Values (mm) Mean	Ray Values (mm) Std. Dev.
1	58.2	7.1	71.4	7.1
2	67.1	4.8	80.3	4.8
3	86.6	5.6	100.3	5.6
4	66.6	6.9	79.8	6.9
5	56.9	9.4	70.1	9.4
6	92.5	7.9	106.4	7.9
7	95.8	6.9	109.7	6.9
8	108.0	6.6	123.6	6.6
9	109.0	6.6	124.6	6.6
10	113.3	7.4	126.9	7.4
11	114.3	6.4	129.3	6.4
12	110.2	6.9	125.6	6.9
13	85.3	5.3	99.0	5.3
14	94.0	6.9	107.9	6.9
15	95.5	6.4	110.3	6.4
16	75.4	8.1	89.3	8.1
17	101.6	8.4	117.2	8.4
18	78.5	10.4	92.4	10.4
19	91.4	9.7	105.3	9.7
20	84.3	6.6	98.0	6.6
21	92.0	7.6	105.9	7.6
22	92.2	7.4	107.0	7.4
23	73.2	8.4	87.1	8.4
24	99.6	7.1	115.2	7.1
25	76.5	7.9	90.4	7.9
26	90.9	6.9	104.8	6.9
27	77.0	8.4	90.5	8.4

	Mean (mm)	Std. Dev. (mm)
Head circumference	565	14.1
Head length	194	6.7
Head breadth	152	5.5
Head height	124	7.2

The BRL algorithm discussed above provided a procedure for sorting subjects into categories according to a four dimensional rule. The physical dimensions of the categories were presented in Table III. For sizing helmets, the total ranges in head dimensions for the two or three size systems are too small to be practically applied. In fact, a useful range is not obtained by any other than the nine size system. Using the nine size system, the 106 subjects were sorted into categories as shown in Table IX. The identifying index is the original subject number. Starting with the nine size system, it was desired to construct a set of headforms which provided generalized shapes to fill in the four dimensional boxes. The intervals between those sizes made the fabrication of nine headforms impractical. Considering the first size, those dimensions correspond closely to the 99th percentile of the total Army population, and thus represent appropriately the largest size. A visual analysis of Table IX, considering the physical intervals between sizes and the number of subjects per size, led to the selection of categories six and nine as practical, four dimensional boundaries. Based on 106 subjects, these sizes led to a distribution of 29% large, 56% medium and 15% small.

After dividing the subjects into sizes, the within -a- size means and standard deviations of the probe readings were computed for the selected three sizes. The objective in generating surfaces was to shape the abstract four dimensional category. After various empirical manipulations of the statistics, it was found that for the small size, the within-a-size mean values of the probe readings yielded a surface which was compatable with its four basic dimensions; for the medium size, the within-a-size mean values were also used; and for the large size, the mean plus one standard deviation was used. This procedure yielded the three sets of probe readings reported in Table X which were used by the sculptor in constructing plaster headforms. The corresponding ray readings are reported in Table XI. The angles of the three moveable probes (Nos. 2, 3, 4) must also be specified; the mean values of 35°, 15° and 0° were used.

The procedure outlined above retained the spatial interrelations of points via the probe positions, and thus overcame one of the main design problems in applying classical anthropometric data. With a set of appropriate probe readings, the sculptor could begin his work.

TABLE IX

SORTING OF SUBJECTS INTO CATEGORIES ACCORDING TO THE NINE SIZE ALGORITHM

Category	Head Dimensions (mm) Circumference	Length	Breadth	Height
1	611	218	170	146
	13			
2	605	213	168	141
	30, 43			
3	599	209	165	139
	11, 31, 77, 101, 106			
4	591	207	163	137
	4, 21, 28, 32, 35, 45, 47, 48, 76, 78, 80, 81, 94, 108			
5	582	205	161	133
	17, 22, 46, 58, 61, 70, 73, 75, 93			
6	581	201	159	132
	7, 14, 18, 19, 23, 25, 41, 49, 51, 60, 62, 68, 72, 84, 88, 92, 97, 103, 105			
7	573	200	158	129
	2, 5, 8, 10, 15, 16, 20, 52, 53, 55, 56, 69, 71, 86, 87, 90, 95, 100, 107, 110, 111			
8	570	197	155	126
	1, 9, 12, 24, 27, 29, 50, 57, 63, 64, 65, 67, 74, 82, 83, 85, 98, 102, 109			
9	557	193	152	123
	3, 6, 26, 34, 37, 44, 54, 59, 66, 79, 89, 91, 96, 99, 104, 112			

TABLE X

PROBE READINGS USED BY THE SCULPTOR (mm)

Probe No.	Small	Medium	Large
1	56.6	58.8	56.6
2	65.0	68.3	71.9
3	85.3	87.1	92.2
4	65.5	66.6	73.4
5	56.4	55.1	56.4
6	89.2	92.2	100.3
7	94.7	95.8	102.6
8	106.2	108.2	114.6
9	107.7	108.7	115.8
10	111.5	112.3	120.7
11	112.0	113.5	120.7
12	107.4	109.7	117.1
13	83.3	86.4	90.7
14	91.7	93.7	100.8
15	93.7	96.3	101.9
16	73.9	74.9	83.6
17	99.3	101.6	110.0
18	76.2	79.0	88.9
19	88.1	92.2	101.1
20	83.1	84.1	90.9
21	90.7	92.0	99.6
22	90.4	91.7	99.6
23	72.4	72.9	81.5
24	98.6	98.8	106.7
25	76.5	74.9	84.3
26	87.9	90.7	97.8
27	72.9	77.2	85.3

TABLE XI

RAY READINGS OF SCULPTURED HEADFORMS (mm)

Probe No.	Small	Medium	Large
1	69.8	72.0	69.8
2	78.2	81.5	85.1
3	99.0	100.8	105.9
4	78.7	79.8	86.6
5	69.6	68.3	69.6
6	103.1	106.1	114.2
7	108.6	109.7	116.5
8	121.8	123.8	130.2
9	123.3	124.3	131.4
10	127.1	127.9	136.3
11	127.6	129.1	136.3
12	123.0	125.3	132.7
13	97.0	100.1	104.4
14	105.6	107.6	114.7
15	108.5	111.1	116.7
16	87.8	88.8	97.5
17	114.9	117.2	125.6
18	90.1	92.9	102.8
19	102.0	106.1	115.0
20	96.8	97.8	104.6
21	104.6	105.9	113.5
22	105.2	106.5	114.4
23	86.3	86.8	95.4
24	114.2	114.4	122.3
25	90.4	88.8	98.2
26	101.8	104.6	111.7
27	86.4	90.7	98.8

b. Sculpturing Technique

The dimensions derived above were used in constructing plaster headforms by Mr. Albert C. Petitto of Hudson, Massachusetts. A set of probe readings was give to Mr. Petitto and, working with a head fixture, he reset the readings and constructed a clay model of the point data. Point data cover the head down to a line running approximately from the glabella to the external canthus to the tragus and back to below the occiput. The face and neck were artistically filled in. Since these headforms were designed specifically for an immediate helmet application, 95 percentile ears (see Alexander and Laubach, 1968) were sculptured on the forms in order to later yield sufficient ear clearance in the helmet.

After the clay model was reworked to achieve dimensional accuracy in terms of the probe readings, a female sectioned mold was fabricated in order to make the required plaster headforms. After casting, the plaster headforms were lightly sanded to the finish dimensions.

The resulting sized headforms are shown in Figure 5. These headforms are the end product of this aspect of the helmet program. The headforms were used by designers to fabricate sized, infantry helmet mock-ups for human factors evaluations.

c. Discussion

The headforms shown in Figure 5 were developed using the head measuring fixture. For a comparison with classical procedures, standard head and face dimensions of the headforms are reported in Table XII. It should be reiterated that the face was artistically sculptured, and no face measurements of subjects were taken in this study.

A comparison of the dimensions in Table XII with White and Churchill (1971) shows that for many dimensions the headforms correspond approximately to the 30th, 75th and 99th percentile values of the Army population.

These are first generation headforms using a new procedure, and additional measurements are planned for two reasons. The sample population was small for any final molds, and some face measurements are desired for other end-item applications.

Figure 5. Plaster Headforms - Front View

TABLE XII

ANTHROPOMETRIC DIMENSIONS OF HEADFORMS* (mm)

No.	Measurement	Small	Medium	Large
	Arcs or Curvatures			
136	Head Circumference	555	572	602
137	Sagittal Arc	355	365	380
138	Minimum Frontal Arc	110	115	120
139	Bitragion-Coronal Arc	330	335	355
140	Bitragion-Crinion Arc	No measurement - no hairline		
141	Bitrag.-Min. Front. Arc	298	300	310
142	Bitragion-Subnasale Arc	285	290	290
143	Bitragion-Menton Arc	325	330	320
144	Bitrag.-Submandib. Arc	305	315	300
145	Bitragion-Inion Arc	No measurement over rigid ears		
146	Bitragion-Posterior Arc	No measurement over rigid ears		
	Depths			
147	Head Length	195	200	209
148	Glabella-Wall	195	197	209
149	Sellion-Wall	195	196	209
150	Pronasale-Wall	225	229	239
151	Subnasale-Wall	208	214	222
152	Lip (Stomion)-Wall	209	217	224
153	Chin (Menton)-Wall	205	207	216
154	Larynx-Wall	157	160	169
155	Ectocanthus-Wall	172	174	183
156	Tragion-Wall	101	101	109
157	Out.Canth.-Otobas. Sup.	72	79	75
158	Sellion-Tragion	96	107	107
159	Tragion-Ant.Chin Proj.	136	142	137
160	Head Diag., Inion-Pron.	195	199	212
161	Head Diag., Menton-Occ.	254	258	259
	Breadth			
162	Head Breadth	151	158	169
163	Bitragion Breadth	148	149	149
164	Biauricular Breadth	200	201	207
165	Max. Frontal Breadth	103	110	113
166	Min. Frontal Breadth	92	98	100

No.	Measurement	Small	Medium	Large
	Heights			
167	Head Height (Trag-Vert)	120	122	129
168	Ectocanthus-Vertex	98	101	107
169	Glabella-Vertex	78	78	87
170	Sellion-Vertex	92	93	97
171	Pronasale-Vertex	130	132	139
172	Subnasale-Vertex	140	143	149
173	Stomion-Vertex	167	167	175
174	Menton-Vertex	209	213	215
	Face			
175	Menton-Crinion	No measurement - no hairline		
176	Face Length (Ment-Sell)	117	120	119
177	Menton-Subnasale	67	68	66
178	Chin Prominence	51	48	49
179	Face Breadth (Bizygom)	147	151	150
180	Bigonial Breadth	127	127	131
181	Biocular Breadth	99	103	106
182	Interpupillary Breadth	70	68	72
183	Interocular Breadth	32	35	36
	Nose			
184	Nose Length (Sell-Subn)	51	56	55
185	Nasal Root Breadth	19	20	19
186	Nose Breadth (Interalar)	37	40	40
187	Nose Prominence	20	22	20
	Mouth			
188	Philtrum Height	16	16	18
189	Lip-to-Lip Height	18	20	19
190	Mouth Breadth, Relaxed	56	57	59
191	Mouth Breadth, Smiling	No measurement - no smile		
	Ear			
192	Ear Length	77	75	76
193	Ear Length above Trag.	32	34	34
194	Ear Breadth	38	39	40
195	Ear Protrusion	25	25	25

* Courtesy of Robert M. White, US Army Natick Laboratories

5. CONCLUSIONS

A three dimensional surface descriptor was designed and fabricated to quantify human head surface geometry. The utility of the surface descriptor (measuring device) in describing human head surface variations was demonstrated. The data generated from the experimental technique were reduced to a form suitable for use by a sculptor in developing sized headforms. Based on the reduced surface data, sized headforms were constructed for use by helmet designers. For the first time, the spatial relationships between anthropometric landmarks were not lost during data reduction. A second generation set of headforms is planned which will be based on a larger population and which will reflect major face dimensions. These second generation headforms will be made from permanent molds using permanent materials. The application of the concepts described in this report to other anatomical shapes, such as the foot, or torso, is straight forward.

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